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Navigating Two-Dimensional and Perspective Views of Terrain

M. St. John
H. S. Smallman
H. M. Oonk
Pacific Science and Engineering Group, Inc.

M. B. Cowen
SSC San Diego

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SPAWAR
Systems Center
San Diego

SSC San Diego
San Diego, CA 92152-5001

EXECUTIVE SUMMARY

Many Command and Control tasks consist of the display of three-dimensional (3-D) objects and environments displayed on flat screens. The question is how to display such information so that it is understood and interpreted in the most effective manner for each different task. We considered the basic qualities and capabilities of two-dimensional (2-D) and 3-D views. We then proposed a distinction between tasks that require shape understanding and tasks that require precise judgments of relative position. We hypothesized that 3-D views are useful for understanding object shape, but 2-D views are more useful for understanding the relative position of objects. In a previous report, we confirmed these hypotheses in two experiments involving simple block shapes. We then extended the results to three experiments involving complex terrain where participants viewed a 7- by 9-mile piece of terrain in 3-D from a 45-degree angle, a 90-degree angle, or in 2-D as a topographic map. In this report, we describe a fourth experiment involving terrain. Participants were asked to estimate the latitude, longitude, and altitude distances between two points on a 7- x 9-mile piece of terrain. We found that these judgments of relative position were most accurate for terrain rendered as a 2-D topographic map. Adding grid and contour lines to the 90-degree angle 3-D views improved performance to the level of the topographic maps. Adding the grid and contour lines to the 45-degree angle 3-D views also improved performance, though not to the level of the topographic maps.

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INTRODUCTION

Many military Command and Control tasks consist of comprehending and interpreting three-dimensional (3-D) objects and environments. For example, air traffic controllers must understand a complex 3-D environment populated with aircraft, air routes, and no-fly zones. Similarly, military tactical officers must understand 3-D environments such as ground and undersea terrain, air routes, and radar zones. Consoles that display data in 3-D seem to provide a natural, and increasingly affordable, solution to these requirements.

A 3-D view is a perspective or oblique view of an object or scene displayed on a standard Cathode Ray Tube (CRT) or Liquid Crystal Display (LCD) panel. The image is two dimensional (2-D), but the viewing angle provides a 3-D perspective. For example, rather than displaying an environment from directly above (i.e., a “bird’s eye” view), perspective view technologies generally display the environment from a 30- or 45-degree angle. While holographic and other true 3-D technologies are progressing, most interest is currently in 3-D *perspective* view displays.

Despite the frequent enthusiasm for them, however, the empirical evidence for using 3-D displays is decidedly mixed. Andre and Wickens (1995) caution that sometimes “users want what’s not best for them.” Across an array of tasks, many studies have found benefits for 3-D perspective over 2-D (Andre, Wickens Moorman, and Boschelli, 1991; Bemis, Leeds, and Winer, 1988; Burnett and Barfield, 1991; Ellis, McGreevey, and Hitchcock, 1987; Haskell and Wickens, 1993; Van Breda and Veltman, 1998). Other studies have found rough parity (Wickens, Liang, Prevett, and Olmos, 1996), and still other studies have found 2-D superior to 3-D (Boyer, Campbell, May, Merwin, and Wickens, 1995; O’Brien and Wickens, 1997; Ware and Lowther, 1997). The various tasks and displays make synthesis difficult, and the results might reflect more on the human performance demands needed to perform a task rather than on the nature of the displays themselves.

Our strategy was to consider the basic qualities of 2-D and 3-D perspective views, what types of information those basic qualities convey, and which tasks require that information. We believe that the main advantage of a 3-D perspective view is the capability to easily convey the shape of complex objects because it integrates all three spatial dimensions into a single view and provides natural depth cues such as relative size, shading, and occlusion. For example, the relative size cue occurs when images of same-sized objects shrink as they recede into the distance, and that shrinkage acts as a cue to place the objects in depth. Interestingly, the effects of perspective projection, while in themselves cues to depth, operate by distorting the image, which can have negative consequences. The main disadvantage of a 3-D perspective view seems to be the distortions created by the perspective projection. For example, foreshortening occurs when an object is rotated toward the line of sight. The length of the object decreases until it disappears altogether[1]. These distortions are exacerbated when objects are small and separated by empty space (e.g., in air traffic control) because the distorting effects of the perspective projection cannot be overcome by the few depth cues that can be displayed on otherwise empty space.

Given these comparative advantages and limitations, the question is when and how to use 2-D and 3-D displays effectively. In our previous studies (St. John and Cowen, 1999; St. John, Oonk, and Cowen, 2000), we proposed a distinction between tasks that require shape understanding and tasks that require precise judgments of relative position. We hypothesized that 3-D views are useful for

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[1] Imagine watching someone lower a telephone pole in your direction. The height dimension of the pole slowly shortens until it disappears entirely, and all you can see is the round top of the pole. This is the effect of foreshortening in a perspective projection.

understanding object shape, but 2-D views are more useful for understanding the relative positions of objects. We confirmed these hypotheses in two experiments involving simple block shapes. We created 10 simple 3-D block shapes (figure 1). Participants viewed blocks in 2-D or a 3-D perspective view and either performed a shape understanding task (identification or mental rotation) or a relative position task (determining directions and distances between objects).

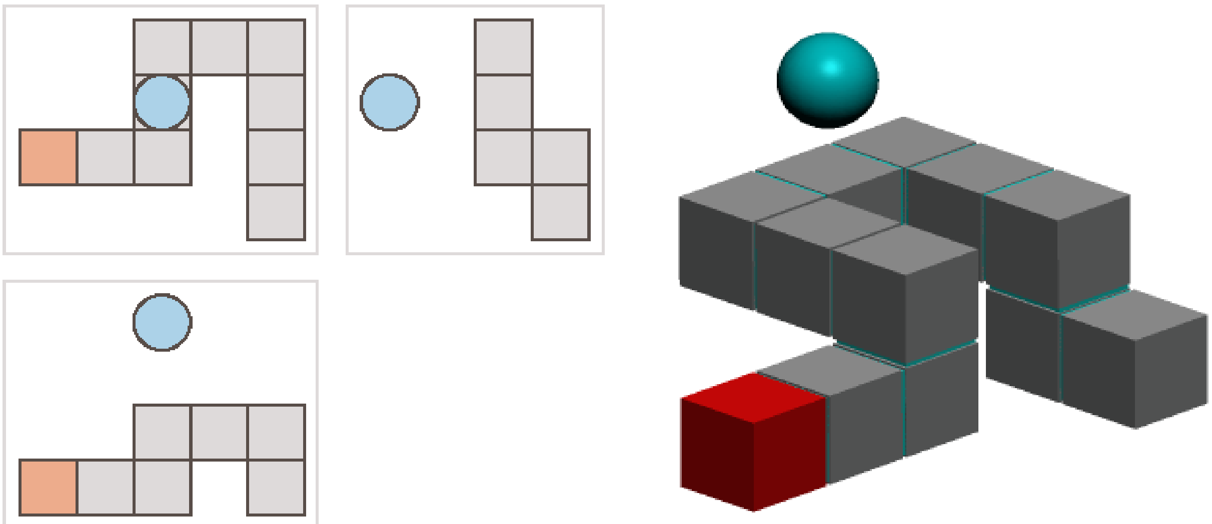


Figure 1. 2-D and 3-D views of an example block and ball used by St. John and Cowen (1999).

In one test of shape understanding, participants were shown a set of 2-D views or a 3-D view of a block, and they were asked to pick out the block from among three real blocks on a table. We found that participants were faster and more accurate using the 3-D view than the 2-D views. In another task, participants were faster and more accurate to mentally rotate 3-D views than 2-D views.

In a test of relative position judgments, participants were shown a 2-D or 3-D view of a block with a ball suspended above it and were asked to indicate which cube of the block lay directly beneath the ball. Note that the location is ambiguous in the 3-D view (figure 1). Accordingly, we provided two 3-D views or three 2-D views (top, front, and side) to help locate the position of the ball. Participants were much faster using the 2-D views.

In another test of relative position and navigation, participants determined how to move from a designated cube (shown in red in figure 1) in the block shape to reach the ball. After the participant correctly identified the location of the ball, compass points appeared on the screen to indicate North, South, East, West, Up, and Down. Participants indicated the number of “cubes” necessary to move in each direction to get from the red cube to the ball. Again, participants performed faster and more accurately using the 2-D views than the 3-D views

The block stimuli were chosen for their simplicity and generality to test the hypothesis while minimizing confounding variables. The simple block stimuli were composed of cubes so that all angles were right angles and all lengths were cube units. These features could be used to compensate for distortions in the 3-D display. For example, no matter how an angle might have appeared in the view, it was known to be a right-angle. The block’s regular angles and lengths benefit the perception of depth in a 3-D perspective display. How might the results generalize to more complex and natural stimuli?

To investigate this issue, we extended our hypothesis in three experiments involving complex terrain (St. John, Oonk, and Cowen, 2000). Participants viewed a 7- by 9-mile piece of terrain in 3-D from a 45-degree angle, a 90-degree angle, or in 2-D as a topographic map (figures 2 and 3). Briefly, in Terrain Experiment 1, participants chose the correct ground-level view from among four alternatives. For this shape understanding task, participants were faster with the 3-D views. In Terrain Experiment 2, participants judged whether or not the position of one location was visible from another location or obstructed by intervening terrain. This task also involved shape understanding because it hinged on understanding the gross layout of the terrain—basically, whether or not a range of hills lay in-between the two points. Again, participants were faster with the 3-D views. In Terrain Experiment 3, participants judged which of two locations was higher. For this relative position task, participants were more accurate with the 2-D topographic maps.

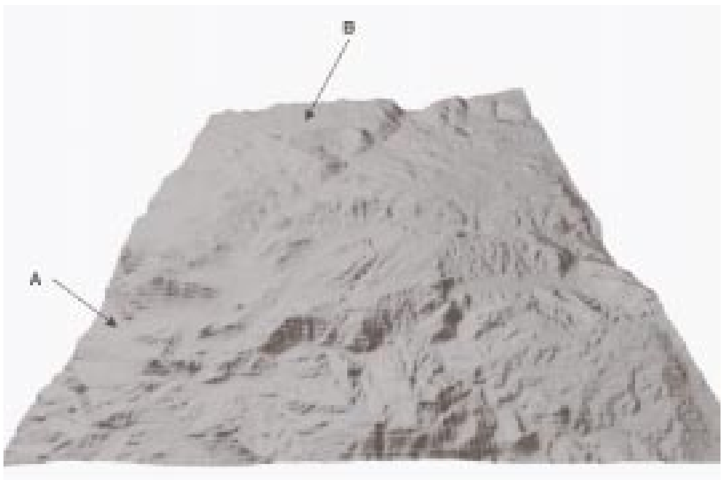


Figure 2. 3-D 45-degree view trial. A and B are two plotted points on the terrain.

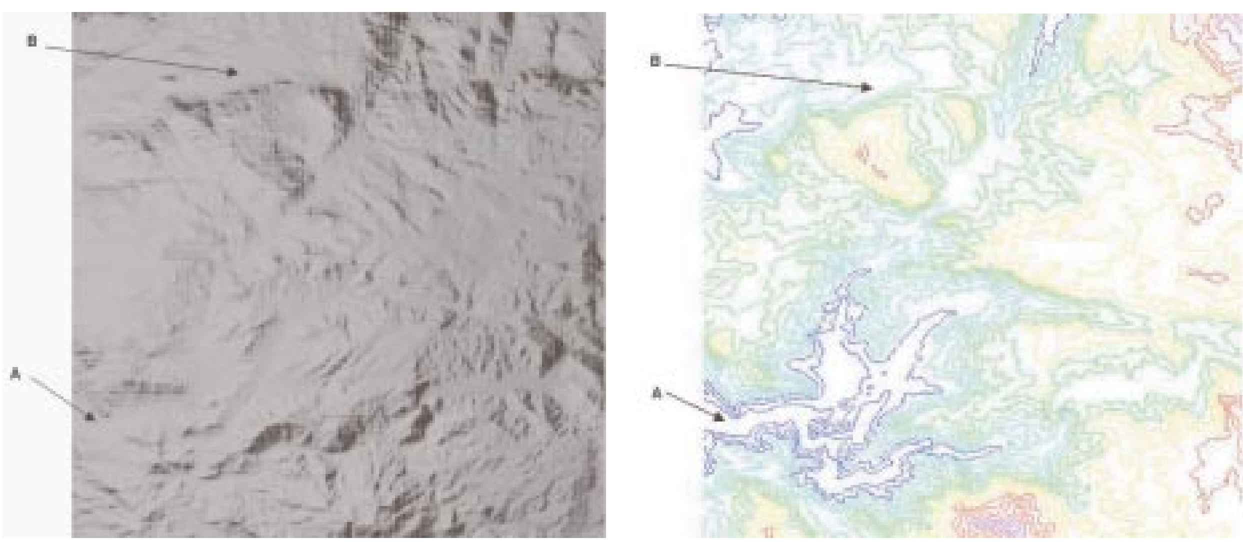


Figure 3. 90-degree view trial (left panel); topographic view trial (right panel). A and B are the same plotted points shown in figure 2.

In Terrain Experiment 4, we more fully tested the hypothesis that 2-D views are better for judging the relative position of two terrain locations. Each participant viewed a 7- by 9-mile piece of terrain viewed in 3-D from a 45-degree angle, in 3-D from a 90-degree angle, or in 2-D as a topographic map. Their task was to estimate the latitude, longitude, and altitude distances between two points on the terrain. We predicted that the 2-D topographic view would be the most useful in estimating the distances between the two points. This task was quite similar to the block navigation task used in St. John and Cowen (1999), which produced a substantial 2-D benefit.

Of secondary interest was whether we could improve the 3-D display by adding artificial cues for distance and altitude. We created new sets of views by rendering grid lines and colored contour lines on the terrain for the 45-degree 3-D view condition (figure 4) and the 90-degree 3-D view condition. We also created one more set of views by rendering the topographic maps with grid lines as well. Our expectation was that the 3-D perspective views would continue to make shape understanding easier while the superimposed grid and contour lines would simplify relative position judgments. For this navigation task, we expected to find that the grid and contour lines would raise performance on all three navigation dimensions of the 3-D views to the level of performance of the topographic views.

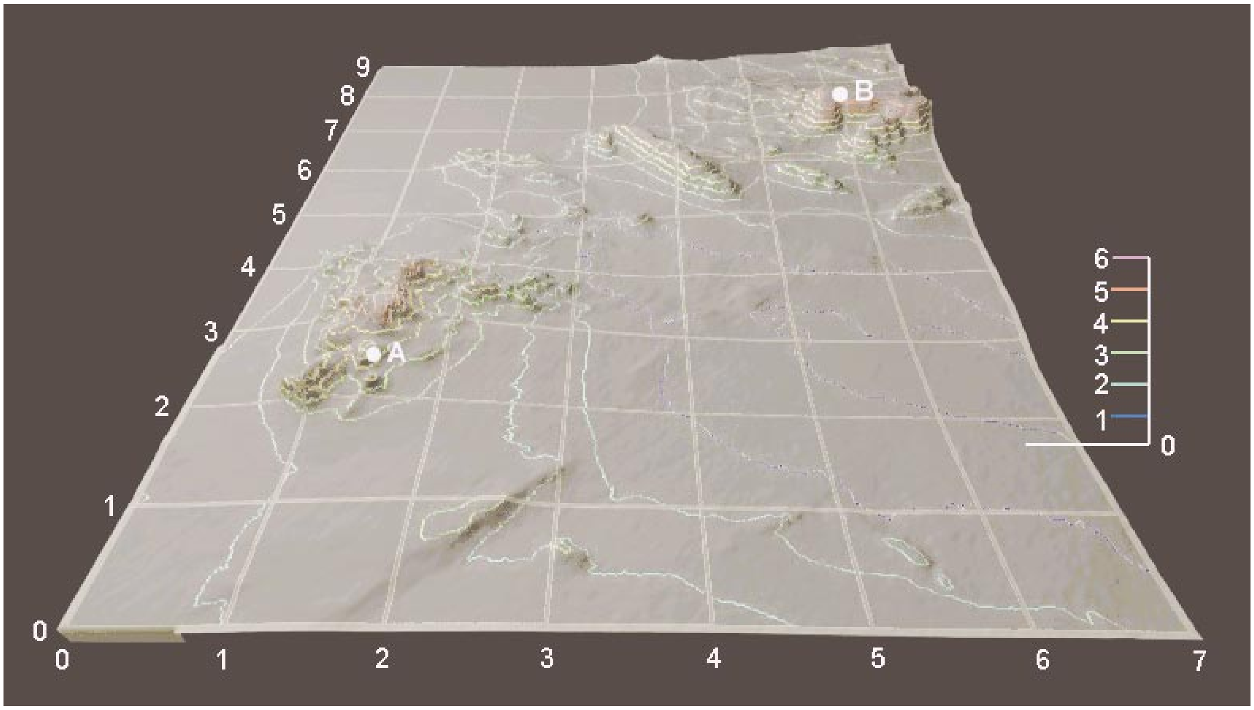


Figure 4. 45-degree view with grid and color contour lines.

METHOD

PARTICIPANTS

The participants were 24 students from local universities who were paid for their participation.

STIMULI

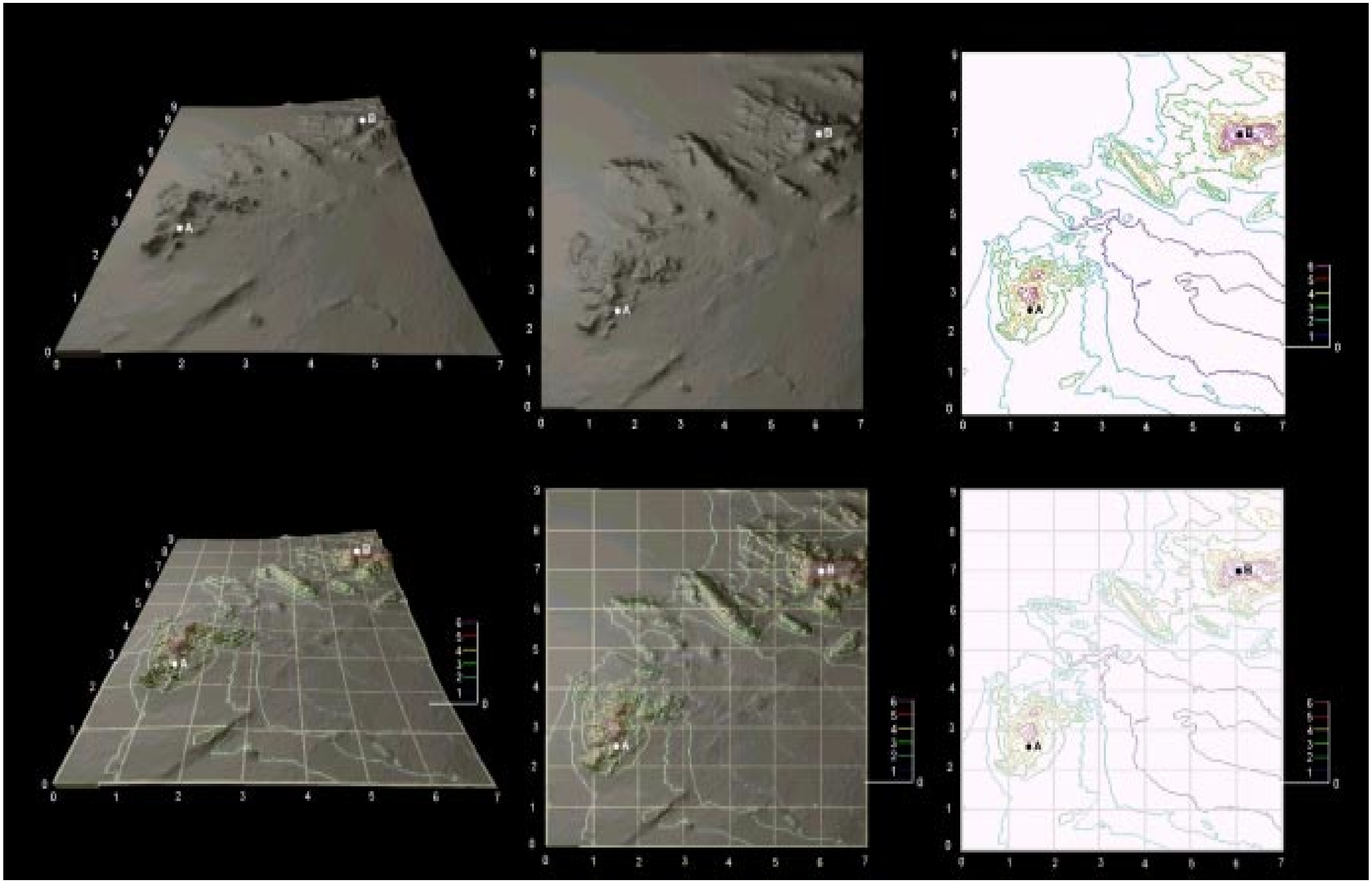
Twenty-six stimuli were created, two from each of the 13 models of terrain used in the previous terrain experiments. To create a stimulus, we plotted two points on the terrain. The two points were chosen randomly from different quadrants of the terrain, and they were labeled A and B (figure 3). Each stimulus was rendered for six different conditions: three base conditions and three base with grid and contour line conditions. The three base conditions were the 45-degree view, the 90-degree view, and the topographic map view. The three base conditions with grid and contour lines were the 45-degree view with grid and contour lines, the 90-degree view with grid and contour lines, and the topographic map view with grid lines. Figure 5 shows screen captures of a sample stimulus by condition.

The stimuli were created from 7- by 9-mile U.S. Geological Survey Digital Elevation models. This terrain area is similar to that found on standard 1:50,000 scale military maps. These models were processed through *MicroDem* to create elevation bitmaps. The topographic maps were created in *MicroDem* by drawing iso-altitude contour lines on the map. Unlike typical military maps, which use numbers to indicate altitude, we color-coded the contour lines to indicate altitude. The program assigned dark blue for the lowest altitude on the map, spanned the color spectrum for intermediate altitudes, and assigned magenta to the highest altitude on the map (figures 3 and 4). An altitude legend showing the six colors of contour lines (numbered from 1 to 6) appeared on the east side of the maps.

The 3-D 45- and 90-degree views were created by importing the elevation bitmaps into *3D Studio*. The camera had a 90-degree field of view and a wide-angle 18-mm lens. An omni-light source (the sun) was placed directly west of the center of the map and at 50 degrees above ground level from the center of the map. Note that the alternative to having the light source at 90 degrees above the center of the map creates an ambiguous image in which changes in altitude are discernable, but direction of change is not. For example, a ridge appears ambiguously as a ridge or a canyon. Having the light source too low toward the horizon creates shadows that are too large and obscure too much terrain. Having the light source directly behind the camera along the line of sight creates a flat-looking landscape that is difficult to understand, and having the light source directly opposite the camera creates shadows that obscure much of the visible terrain. Similar to our previous experiments, we selected a light source that was roughly 50 degrees above ground level and 90 degrees to the left or right of the camera for optimal depth perception.

For the 3-D 90-degree views (figure 3, right), the camera was suspended 3.5 miles directly above the center of the map—high enough to view the entire map. For the 3-D 45-degree views (figure 2), the camera was south of the map so that the entire map was visible, maintaining a 45-degree angle between ground level and the line of sight to the center of the map.

45-DEGREE 90-DEGREE TOPOGRAPHIC



NO GRID

GRID

Figure 5. Screen captures of a sample stimulus by condition.

In the base conditions (without grid or contour lines), 1-mile markers (figure 6, bottom) were arranged along the south and west sides of all views. Altitude was indicated on the topographic maps by showing a color scale to the right of the map. The color scale was labeled from 1 for dark blue to 6 for magenta. Altitude was indicated verbally on the 3-D views as a scale of 1 to 6, with 1 the lowest point on the map and 6 the highest point on the map.

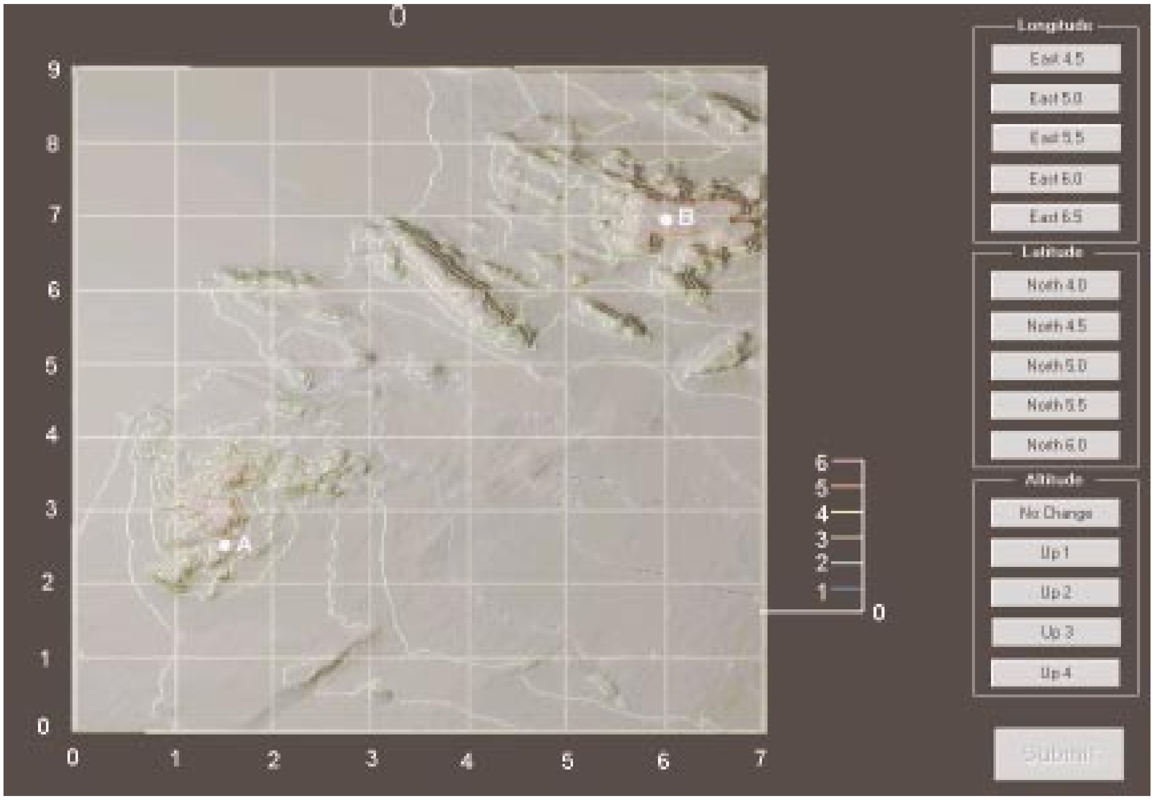
In the grid and contour lines conditions, latitude and longitude grid lines at 1-mile increments were rendered on top of the map surfaces. For the 3-D 45-degree views, the grid lines followed the shape of the terrain (figure 4). The colored contour lines from the topographic views were rendered onto the terrain on the 90-degree view (figure 6, top) and the 45-degree view (figure 4), and the altitude legend was added to each view. We were concerned that thin contour lines would not be easily visible, but that thick lines would obscure too much terrain. Consequently, we rendered both a thick-line (2-pixel) version and a thin-line version (figure 4) for each map. Participants saw half of the maps with thick lines and half with thin lines in a counterbalanced fashion. No performance differences between thick and thin lines were found.

To the right of the maps, three sets of five buttons were arranged vertically (figure 6). The buttons in each set displayed multiple choice answers for each dimension (latitude, longitude, and altitude). The choices for latitude and longitude were arranged in half-mile increments, and the choices for altitude were arranged in one-color step increments.

PROCEDURE

The stimuli were displayed one at a time on a 15-inch color LCD panel. The participants' task was to view the terrain and select the correct distances between points A and B. Participants responded by using a mouse to select a longitude button, a latitude button, and an altitude button. If the answer on any dimension was incorrect, the computer would sound a buzzer, highlight the incorrect dimension(s), and gray out the incorrect answer(s) that the participant had made. Thus, participants could quickly focus on the problem dimensions. We provided this feedback to ease frustration, because this task was very difficult. After three incorrect attempts, the computer advanced to the next trial. Response times and errors were recorded for each trial.

The 26 stimuli for each type of view (45-degree, 90-degree, and topographic) were grouped into blocks, and the order of the blocks was counterbalanced among participants. Half of the participants (n = 12) saw the views in the base conditions, and half (n = 12) saw the views in the grid and contour line conditions.



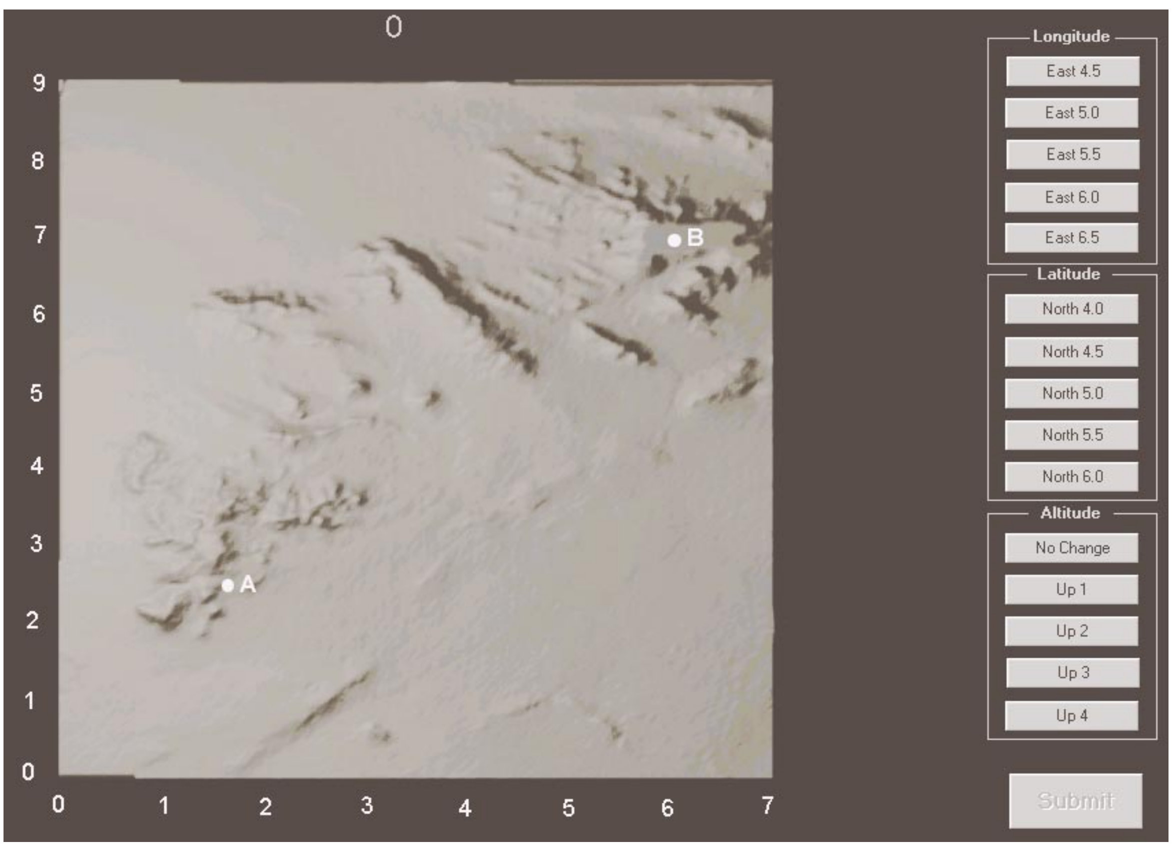


Figure 6. Two 90-degree views of same terrain with and without grid and color contour lines.

RESULTS

BASE CONDITIONS

Figure 7 shows a scatter plot of the Response Time (RT) to find the correct answer (within three attempts) by the proportion correct on the first attempt. The task was very difficult for most participants. The average proportion correct score was 0.38. Proportion correct scores for the three views were statistically different, $F(2, 22) = 61.7$, $p < .0001$. Post-hoc tests revealed that participants were least accurate with 45-degree views, more accurate with 90-degree views, and most accurate with the topographic views ($p < .0005$). The scatter plot of the participants' scores in figure 6 shows very little overlap of accuracy scores, which underscores how different performance was on the different conditions. Total RT for the three views was also statistically different, $F(2, 22) = 13.5$, $p < .0002$. Post-hoc tests revealed that participants were slower with the 45-degree views (53 seconds) than the 90-degree (32 seconds) and topographic views (36 seconds).

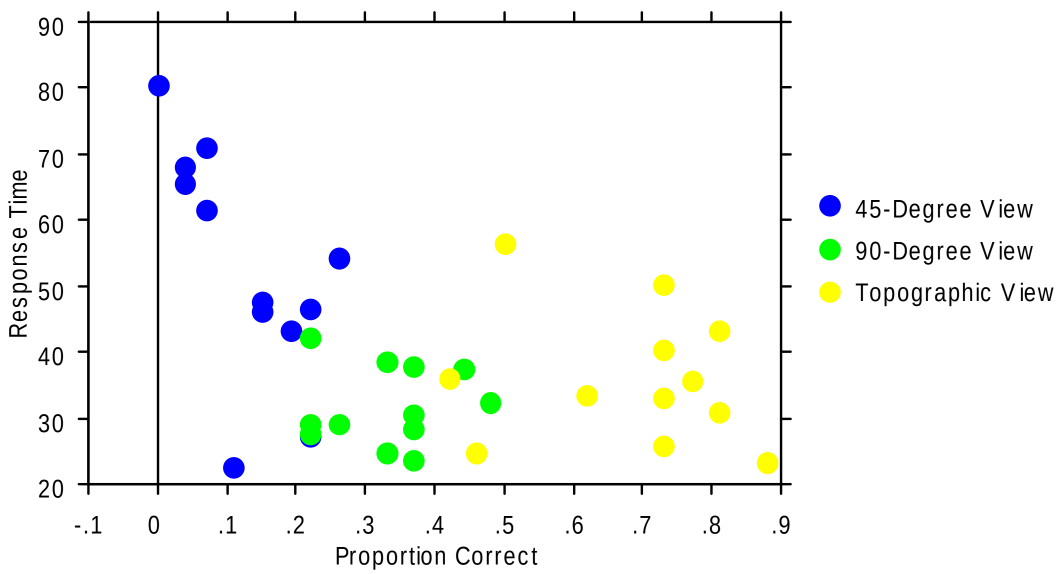


Figure 7. Scatter plot of RT (proportion correct by condition).

Figure 8 shows the proportion correct scores on the first attempt for the base conditions and for the base grid and contour line conditions. The blue columns represent the proportion correct for a specific dimension (e.g., longitude, latitude, and altitude) and the red horizontal bars represent the proportion correct on the first attempt for all dimensions (i.e., must answer all three dimensions correct on the first attempt). In the base conditions, all three dimensions were judged poorly in the 45-degree view condition, and only the altitude dimension was judged poorly in the 90-degree 3-D view condition. All three dimensions were judged satisfactory in the topographic view condition. The interaction of view and dimension was statistically significant, $F(4,44) = 22.8$, $p < .0001$.

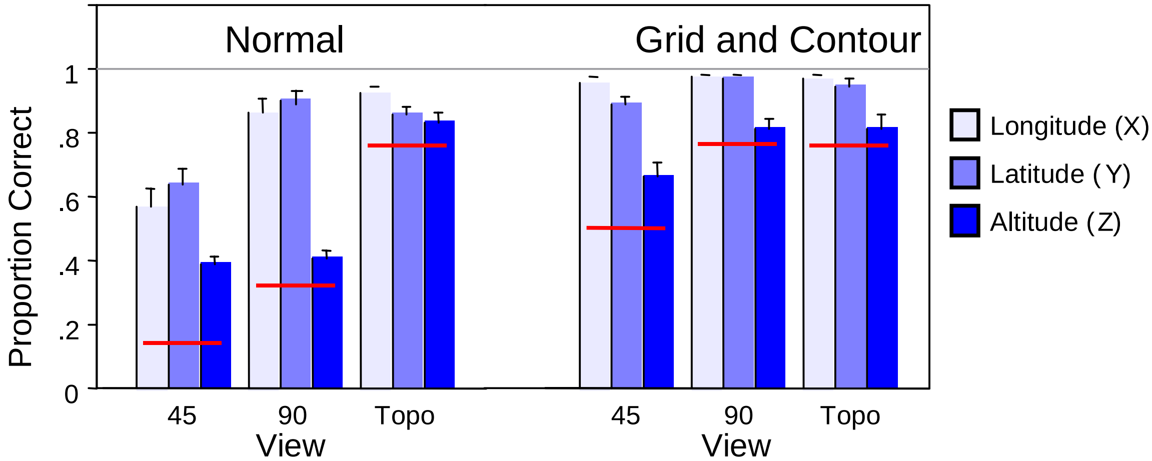


Figure 8. Proportions correct on the navigation task.

GRID AND CONTOUR LINE CONDITIONS

Augmenting the base conditions with the grids and contour lines substantially helped overall accuracy, which nearly doubled to an average of 0.69, $F(1,22) = 71.8$, $p < .0001$. Interestingly, after adding the grid and contour lines, altitude remained the worst dimension overall, with only an average of 65% correct for altitude compared with 88% correct for longitude and latitude, $F(2,22) = 50.1$, $p < .0001$. The interaction of adding grid and contour lines to base conditions was also statistically significant, $F(2, 44) = 17.4$, $p < .0001$. Most improvement was from the 45-degree view condition, which increased from an average proportion correct score of 0.13 to 0.56. However, the 45-degree condition continued to have the worst accuracy performance, even after adding grid and contour lines, $F(2, 22) = 10.3$, $p < .0007$. Meanwhile, the 90-degree 3-D views with the grid and contour lines reached the level of accuracy of the 2-D topographic conditions (with or without grid lines).

Adding the grid and contour lines did not reliably improve response times. However, the interaction of adding grid and contour lines to the different base view conditions was statistically significant ($F(2,44) = 3.27$, $p < .05$), with all the improvement from the 45-degree condition. However, despite this improvement, the 45-degree views (39 seconds) were answered slower than the 90-degree views (30 seconds) or the topographic views (33 seconds), $F(2,22) = 4.8$, $p < .02$.

Our belief that adding grid and contour lines to the 3-D views would benefit performance for relative position tasks was not completely supported. While the additions of grid and contour lines significantly improved performance with the 45-degree views, performance did not reach the level of 2-D topographic maps. However, adding grid and contour lines to the 90-degree views increased performance to the level of the 2-D topographic maps. The 90-degree view looks very promising for shape understanding and relative position judgment tasks, especially with the addition of grid and contour lines.

DISCUSSION

We found that judging the precise distance between two points was performed better using 2-D topographic views than 3-D views. This result, combined with our previous findings with terrain (Andre et al., 1991) and simple block and ball stimuli (Andre and Wickens, 1995) suggest that 2-D views are generally superior to 3-D views for making precise relative position judgments. Three-dimensional perspective views, however, appear superior for understanding the shapes of objects and the rough layout of scenes and terrain (Andre et al., 1991; Andre and Wickens, 1995). Together, these findings have important implications for the design of visualization software from maps to structural illustrations. Three-dimensional views should be for conveying shape and rough layout, but 2-D views should be used when precision judgments of distance and angle are required.

Why might performance differences exist between the types of views? Three-dimensional views are useful for shape and layout understanding because they (1) integrate all three dimensions into a single rendering, (2) are receptive to supplementary depth cues, and (3) show features of an object that would be invisible in a normal 2-D view. The integration of all three dimensions into a single rendering is useful for understanding shape. With 2-D views, no single view can provide information about all three dimensions of an object. Information about the shape of an object or scene must then be combined mentally from at least two separate views. This mental operation is both difficult and time-consuming. A perspective view is easier to use because it integrates the dimensions into a single view. Any task that requires perception of the 3-D shape of an object should therefore benefit from a 3-D perspective view.

Two-dimensional views are useful for judging relative positions because the normalized viewing angles minimize distortions caused by the perspective projection—what is visible is represented faithfully. Also, ambiguity is confined to a single dimension. For example, in a top-down view, only altitude is ambiguous because it is not represented at all. Confinement of ambiguity to a single non-represented dimension seems to provide better opportunities to deal with the ambiguity. For example, a user can easily switch among a set of 2-D views to obtain undistorted information about each dimension of interest. In contrast, 3-D views spread the ambiguity across all three dimensions so that resolving those ambiguities requires substantial effort, as demonstrated in our experiment. Confining the ambiguity to a single dimension while faithfully representing the other two dimensions, as in a 2-D display, might be more usable for locating objects than showing three vague, but integrated, dimensions.

For complex tasks that involve aspects of shape understanding and relative position judgments, 2-D and 3-D views might be useful. We are exploring several methods of combining views. As described above, we tested the possibility of combining the 3-D views with contour lines from the topographic maps. We found that adding 2-D view features improved the usefulness of the 3-D views for locating objects. We are encouraged by the potential of combined views for shape understanding and relative position tasks.

We are beginning to explore a 2-D/3-D design concept called “Orient and Operate.” Users *orient* to the layout of a scene using a 3-D view, but then switch to 2-D views to interact with and *operate* on the scene. A 3-D view would be used to gain a basic grasp of the scene, and then a 2-D view would be used for finding the locations of the objects. We are considering many design alternatives for realizing this concept, such as presenting both 3-D and 2-D views simultaneously or allowing the user to select the 45-degree viewing angle first, then rotate the scene to a top-down or side view. We will discuss the viability of “Orient and Operate” design alternatives in our next report.

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M. St. John
H. S. Smallman
H. M. Oonk
Pacific Science and Engineering Group, Inc.

M. B. Cowen
SSC San Diego

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14. ABSTRACT

Many Command and Control tasks consist of the display of three-dimensional (3-D) objects and environments displayed on flat screens. The question is how to display such information so that it is understood and interpreted in the most effective manner for each different task. The authors consider the basic qualities and capabilities of two-dimensional (2-D) and 3-D views. This report describes an experiment involving terrain. Participants were asked to estimate the latitude, longitude, and altitude distances between two points on a 7- by 9-mile piece of terrain. Judgments of relative position were most accurate for terrain rendered as a 2-D topographic map. Adding grid and contour lines to the 45-degree angle 3-D views also improved performance, though not to the level of the topographic maps.

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Program Operations Center
Corona, CA 91718-8000

Fleet Antisubmarine Warfare Training Center
San Diego, CA 92147-5199

Naval Air Warfare Center,
Training Systems Division
Orlando, FL 32826-3224

Navy Personnel Research and
Development Center, Millington Office
Millington, TN 38054-5026

Office of Naval Research
Arlington, VA 22217-5660

Pacific Science and Engineering Group
San Diego, CA 92122 (5)

University of California, Santa Barbara
Department of Psychology
Santa Barbara, CA 93106

Instructional Science & Development Inc.
Pensacola, FL 32507

University of Illinois
Department of Psychology
Champaign, IL 61820

Defense Information Systems Agency
Reston, VA 20191-4357

Assistant Secretary of Defense for
C3I/CISA
Arlington, VA 22202

The Chairman Joint Chiefs of Staff
Washington, DC 20318-6000